UNITED STATES PATENT APPLICATION FOR:

METHOD AND APPARATUS FOR GENERATING CHARGE FROM A LIGHT PULSE

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METHOD AND APPARATUS FOR GENERATING CHARGE FROM A LIGHT PULSE

GOVERNMENT RIGHTS IN THIS INVENTION

[0001] This invention was made with U.S. government support under contract number NRO000-02-C-0394 awarded by the National Reconnaissance Office. The U.S. government has certain rights in this invention.

CROSS-REFERENCE TO RELATED APPLICATIONS

[0002] This application claims benefit of United States provisional patent application serial number 60/434,099, filed December 17, 2002, and is a continuation-in-part of co-pending U.S. patent application serial number 10/107,966, filed March 27, 2002, each of which is incorporated by reference herein in its entirety.

BACKGROUND OF THE INVENTION

Field of the Invention

[0003] The present invention generally relates to sensing, receiving, and processing light signals and, more particularly, to generating charge from a light pulse.

Description of the Related Art

[0004] In general, three-dimensional imaging systems employing active sources, such as laser detection and ranging (LADAR) systems, suffer from one primary problem: sensors designed to obtain two-dimensional amplitude images are not adept at rendering an image in three-dimensions. While there have been many attempts at adopting such two-dimensional sensors to three-dimensional imaging, such systems have always been found to be lacking, particularly in range resolution and sensitivity.

[0005] For example, one type of known three-dimensional imaging approach uses very high pixel sampling rates in various forms to determine time of flight for the laser pulse to travel from the laser to a target and on to a detector. The

time of flight of an illuminating pulse is very difficult to measure since one nanosecond of time resolution is required to achieve one foot of depth resolution. As such, these systems typically employ high-speed counting and high-speed clocking circuits for operation. In cases where a depth resolution of inches is necessary (i.e., sub-nanosecond time differences must be resolved), the required operating speed of these counting and clocking circuits is difficult to achieve. Other known systems measure phase shifts between the illuminating signal and the signal returned from the target. These systems are susceptible to noise and provide inadequate sensitivity when the signal reflected from the target is very weak.

[0006] Therefore, there exists a need in the art for a method and apparatus for accurately resolving sub-nanosecond differences between times-of-arrival of light pulses.

SUMMARY OF THE INVENTION

[0007] The present invention is a device for resolving relative times-of-arrival of a plurality of light pulses comprising a plurality of drift-field detectors. Each drift-field detector comprises a light sensor and a semiconductor drift region. Each light sensor generates an electrical charge from at least one of the plurality of light pulses. Each semiconductor drift region receives the electrical charge from its respective light sensor and, pursuant to an electric field therein, produces a spatial charge distribution. The spatial charge distribution for each of the semiconductor drift regions is stored in an analog storage device associated therewith. In one embodiment of the invention, the analog storage devices comprise charge-coupled device (CCD) registers. The relative positions of the charge distributions in the semiconductor drift regions can be used to calculate the relative times-of-arrival of the light pulses. The present invention can be used in three-dimensional imaging applications, where the relative times-of-arrival of reflected light pulses are used to calculate the depth of the scene.

[0008] Another aspect of the invention relates to a method and apparatus for generating charge from a light pulse. In one embodiment of the invention, a

light sensor includes an active region for generating an electric charge in response to a light pulse. A drift region is formed within a substrate and receives the electric charge from the light sensor. A spatial charge distribution is produced within the drift region in response to an electric field. The drift region includes an outer edge and an inner edge. The volume of the drift region decreases from the outer edge to the inner edge.

BRIEF DESCRIPTION OF THE DRAWINGS

[0009] So that the manner in which the above recited features of the present invention can be understood in detail, a more particular description of the invention, briefly summarized above, may be had by reference to embodiments, some of which are illustrated in the appended drawings. It is to be noted, however, that the appended drawings illustrate only typical embodiments of this invention and are therefore not to be considered limiting of its scope, for the invention may admit to other equally effective embodiments.

[0010] Figure 1 depicts a block diagram showing an exemplary three-dimensional imager incorporating an array of drift-field detectors of the present invention;

[0011] Figure 2 depicts a schematic diagram showing a single drift-field detector;

[0012] Figure 3 depicts a block diagram showing one embodiment of analog storage devices for use with the present invention;

[0013] Figures 4A through 4C are graphs showing charge distributions in drift regions of three drift-field detectors of the present invention;

[0014] Figure 5 illustrates multiple light pulses having different times-of-arrival striking a signal drift-field detector of the present invention;

[0015] Figure 6 is a plan view depicting another exemplary embodiment of a drift field detector;

[0016] Figure 7 is a cross-sectional view of an exemplary embodiment of the drift field detector of Figure 6 taken along the line 7—7;

[0017] Figure 8 is a plan view depicting yet another exemplary embodiment of a drift field detector; and

[0018] Figure 9 is a cross-sectional view of an exemplary embodiment of the drift field detector of Figure 9 taken along the line 9—9.

[0019] To facilitate understanding, identical reference numerals have been used, wherever possible, to designate identical elements that are common to the figures.

DETAILED DESCRIPTION OF THE INVENTION

[0020] The present invention is an apparatus for resolving relative times-of-arrival of light pulses without relying upon high-speed counting and clocking circuitry. As described in detail below, the present invention comprises a plurality of drift-field detectors generally formed in an array. Each drift-field detector comprises a semiconductor drift region coupled to a light sensor. The present invention resolves relative times-of-arrival of light pulses by measuring the distance a photo-generated charge packet moves through an electric field in the drift region for each drift-field detector. The apparatus of the present invention can be used in three-dimensional imaging applications, where a drift-field detector is used at each pixel of a three-dimensional image sensor and the time-of-arrival of a reflected light pulse incident on each pixel in the imaging array is used to produce a three-dimensional image. By eliminating clocking limitations, the present invention can resolve sub-nanosecond time-of-arrival differentials, advantageously providing depth information in an imaged scene to an accuracy of a centimeter or better. Those skilled in the art will appreciate that the present invention is useful in any application that requires resolving relative times-of-arrival of light pulses with high accuracy.

[0021] Figure 1 depicts a block diagram showing an exemplary three-dimensional imaging system 100 incorporating the apparatus of the present

invention. The system 100 comprises a light source 102, a drift-field detector array 104, a processor 106, control circuitry 107, and a display 108. The light source 102 produces light pulses 124 to illuminate a target 118. The light pulses 124 reflect from the target 118 and are focused onto the drift-field detector array 104 by an optical lens 116. The detected light signals are processed by processor 106, under control of control circuitry 107, for display as an image on display 108.

[0022] More specifically, the light source 102 comprises a light emitting diode (LED) or laser source capable of emitting a pulse of light 124 of a particular wavelength. The wavelength of the light pulse 124 depends upon the particular application of the imager 100, and is generally in the range between ultraviolet and infrared wavelengths. As shown, the light pulse 124 passes through optical lens 114 before traveling to a target 118. Alternatively, the light source 102 can transmit the light pulse 124 to the target 118 without the aid of the optical lens 114 if the light source 102 is sufficiently powerful.

[0023] Axis 128 represents the distance between the target 118 and the system 100, with the origin at the system 100. The target 118 comprises a first portion 130 that is a distance Z_1 from the system 100, a second portion 122 that is a distance Z_2 from the system 100, and a third portion 120 that is a distance Z_3 from the system 100. The light pulse 124 illuminates the target 118, causing at least some of the light to be reflected back toward the system 100 in the form of reflected light 126. The reflected light comprises a multiplicity of scattered light pulses. The reflected light 126 passes through optical lens 116, which focuses the reflected light 126 onto the drift-field detector array 104. The drift-field detector array 104 comprises a plurality of drift-field detectors 110_1 through 110_N (collectively 110) and respective analog storage devices 112_1 through 112_N (collectively 112). A 4x4 array of drift-field detectors 110 is shown for simplicity, but the present invention can have an MxN array of drift-field detectors 110, where M and N are integers having a value of 1 or more. The optical lens 116 operates such that a reflected light pulse from a point on the surface of the target 118 will only fall upon the i^{th} drift-field detector 110_i in the array 104 that is focused upon such point. That is, each of the drift-field

detectors 110 has a field of view (FOV) that dictates which light pulses in the reflected light 126 will be detected by a given drift-field detector 110_i.

[0024] Figure 2 depicts a schematic diagram showing an individual drift-field detector 110_i in accordance with the present invention. The drift-field detector 110_i comprises a light sensor 204 and a semiconductor drift region 202. The light sensor 204 comprises a light sensitive detector, such as a silicon photodetector (e.g., a PIN photogate detector). The choice of light sensitive detector for the light sensor 204 is dictated by the wavelength of operation. For example, if the light source 102 of the system 100 transmits an illuminating pulse in the ultraviolet or visible spectrum, then the light sensor 204 can comprise a silicon photodetector. If the light source 102 of the system 100 transmits an illuminating pulse in the short-wave infrared light (SWIR) spectrum, the light sensor 204 can comprise a platinum silicide detector, or a III – IV detector and appropriate readout circuitry (e.g., control circuitry 107). In this manner, the present invention can provide for an "eye-safe" imaging system. In any case, all that is required is for the light sensor 204 to generate a charge proportional to the amount of incoming photon energy incident upon it, and that this charge be injected into the drift region 202 in the form of electrons or holes, as described below.

[0025] In one embodiment, the drift region 202 comprises an N-buried channel formed in silicon having a known length. Alternatively, the drift region 202 can be formed of P-type silicon, wherein holes are injected into the drift region 202 from the light sensor 204. In either case, the drift region 202 is electrically coupled to the light sensor 204 such that charge (be it electrons or holes) is injected into the drift region 202 from the light sensor 204 when light is detected. In one embodiment, the light sensor 204 and the drift region 202 are formed monolithically on a silicon substrate. This allows for production of the drift-field detector 110_i in standard silicon foundries using standard design rules for cost-effective fabrication. In addition, the appropriate detector readout circuitry (e.g., control circuitry 107) can be incorporated into the same silicon substrate as the drift region. Alternatively, the light sensor 204 can be fabricated apart from the drift region 202 and then be bump bonded thereto.

[0026] A variable voltage source 206 is coupled on one end to the light sensor 204, and on the other end to the drift region 202. The variable voltage source 206 generates an electric field in the drift region 202. The voltage of voltage source 206 is controlled by processor 106 through control circuitry 107. In the embodiment shown, the variable voltage source 206 is coupled using ohmic connections. Alternatively, the variable voltage source 206 can be coupled to the light sensor 204 and drift region 202 via a plurality of gates (not shown) disposed thereon for generating the electric field. In any case, the variable voltage source 206 is controlled via switch 208. Switches 208 for the drift-field detectors 110 are controlled via control circuitry 107. In one embodiment, control circuitry 107 comprises a CMOS multiplexer capable of selectively controlling each switch 208 in the array 104, as well as the voltage applied by respective variable voltage source 206. In this manner, the processor 106 can control the electric field for specific ones of the drift-field detectors 110. In such an embodiment, the CMOS multiplexer can be formed monolithically with the light sensors 204 and/or the drift regions 202.

[0027] In addition, the drift region 202 is associated with an analog storage device 112_i. The analog storage device 112_i can comprise a charge-coupled device (CCD) register having a plurality of bins 214 formed therein. In such an embodiment, the analog storage device 112_i can be formed monolithically with the light sensor 204 and/or the drift region 202. CCD transfer gate 210 acts as the interface between the drift region 202 and the analog storage device 112_i for the transfer of charge therebetween. Each CCD transfer gate 210 is controlled by control circuitry 107. In one embodiment, control circuitry 107 comprises a second CMOS multiplexer capable of selectively controlling each CCD transfer gate 210 in the array 104. In this manner, the processor 106 can control the charge transfer between specific ones of the drift-field detectors 110 and their respective analog storage device 112. Again, the second CMOS multiplexer can be formed monolithically with the other components of the array 104.

[0028] In operation, a light pulse strikes the surface of the light sensor 204 and photon energy is converted into electric charge. The charge integration time for the light sensor 204 can be gated using control gates and a charge dump drain

(not shown). The electric charge is injected into the drift region 202. The variable voltage source 206 supplies a voltage differential across the drift region 202 such that an electric field is produced therein. This electric field is enabled and disabled by switch 208. When the electric field is applied, the charge injected into the drift region 202 moves through the semiconductor material at a rate determined by the electric field combined with thermal diffusion. This rate also depends upon other factors, such as the type and temperature of the semiconductor material. Thus, a charge distribution will form in the drift region 202 having a certain shape and position. When the electric field is removed (by opening switch 208), the charge distribution will remain fixed within the drift region 202, but the shape will continue to disperse due to thermal diffusion. The velocity of electrons due to thermal diffusion, however, can be adjusted to be much less than the velocity of electrons where the electric field is applied to the drift region 202.

[0029] In order to retain the position and shape of the charge distribution in the drift region 202, the charge distribution is transferred to the analog storage device 112_i. The position of the charge distribution in the drift region 202 essentially "freezes" for a time long enough to move the charge from the drift region 202 to the analog storage device 112_i. In the present embodiment, the analog storage device 112_i is a CCD register having a plurality of bins 214 capable of storing charge. Specifically, once the electric field is removed from the drift region, CCD transfer gate 210 operates to transfer the charge distribution from the drift region 202 to the plurality of bins 214. The number of bins 214 depends on the desired resolution of the charge distribution. That is, more bins 214 in the CCD register results in the storing of more detail of the shape and position of the charge distribution in the drift region 202. In one embodiment, the transfer time from the drift region 202 to the bins 214 is in the range of 5 to 20 ns at room temperature to keep the thermally induced dispersion in the drift region within desirable limits. The operation of the analog storage devices 112 is described in more detail below with respect to Figure 3.

[0030] Returning to Figure 1, since portion 120 of the target 118 is farther away from the system 100 than portion 122, light reflected from portion 120 will take

longer to reach the system 100 than light reflected from portion 122. Thus, different light pulses in the reflected light 126 will arrive at the system 100 at different times. The difference between times-of-arrival of light pulses can be used to determine the depth of the scene. The present invention can resolve the relative times-of-arrival of light pulses incident on an array of drift field detectors 104 using the charge distribution in each of the drift field detectors 110.

[0031] Specifically, each of the drift-field detectors 110 is activated (i.e., the switch 208 is closed and the electric field applied in each drift region 202 via control circuitry 107) at some time t_{start} after the illuminating pulse 124 has been transmitted. This time can coincide with the arrival of the first light pulse reflected from the target 118, but this does not necessarily have to be the case. The time t_{start} can coincide with the arrival of the first light pulse of interest that is reflected from the target 118. As described more fully below, the time difference between when the illuminating pulse 124 is transmitted and when the drift-field detectors 110 are activated controls the range of the system 100.

[0032] Assume that one particular drift-field detector 110_1 within the array 104 is focused upon portion 130 of target 118. The associated drift-field detector 110_1 will detect the reflected light pulse and generate a charge packet in response to the incoming photon energy. This charge is injected into the associated drift region 202 and begins to drift in response to the electric field. At some later time, a reflected light pulse will arrive at optical lens 116 from portion 122 of target 118 and will be detected by another drift-field detector 110_2. Again, the charge will be injected into the drift region 202 of this second drift-field detector 110_2 and will begin to drift. Hitherto the charge in the drift region 202 of the first drift-field detector 110_1 has continued to drift. In a similar fashion, another drift-field detector 110_3 will detect a reflected light pulse from portion 120 of target 118 at yet a later time. This charge is injected into the drift region 202 of this third drift-field detector 110_3 and will begin to drift. Again, hitherto the charge in both drift regions 202 of the first and second drift-field detectors 110_1 and 110_2 has continued to drift. Finally, at some time t_{stop} the electric fields in the drift regions 202 of the drift-field detector array 104 will be turned off, and all drifting

of charge will cease (with the exception of thermal diffusion, as described above).

[0033] As described above, the charge distributions in the drift-field detectors 110 are transferred to analog storage devices 112 at some time after t_{stop}. The processor 106 can then read the charge from the analog storage devices 112 via control circuitry 107. Once read out, the processor 106 uses the relative positions of the charge distributions in the drift regions 202 to calculate the relative times-of-arrival of the light pulses. Given the relative times-of-arrival of the light pulses, the processor 106 can compute a three-dimensional image that can be shown on display 108.

[0034] Figures 4A through 4C are graphs showing charge distributions in drift regions of the three drift-field detectors 110_1, 110_2, and 110_3. Figures 4A through 4C share common axes. Axis 402 represents the carrier density in the drift region 202 having units of electrons per μm^2. Axis 404 represents position in the drift region 202 having units of μm. Assume each drift region has a length of approximately 100 μm and an electric field of approximately 10 V/100 μm. Assume also that time t_{start} is time $t = 0$, and time t_{stop} is time $t = 10$ ns. Finally, assume that the first light pulse arrives at time $t = 0$, the second light pulse arrives at time $t = 8$ ns, and the third light pulse arrives at time $t = 9$ ns.

[0035] Figure 4A shows the charge distributions right after the electric fields are removed from the three drift regions at time $t = 10$ ns. Curve 410 represents the charge distribution in the drift region 202 of the first drift-field detector 110_1, curve 408 represents the charge distribution in the drift region 202 of the second drift-field detector 110_2, and curve 406 represents the charge distribution in the drift region 202 of the third drift-field detector 110_3. After 10 ns of the applied electric field, the centroid of the charge distribution 410 has drifted to a position of 100 μm. After 2 ns of the applied electric field, the centroid of the charge distribution 408 has drifted to a position of 20 μm. Finally, after 1 ns of the applied electric field, the centroid of the charge distribution 406 has drifted to a position of 10 μm. The shape of each charge distribution spreads due to thermal diffusion as it drifts due to the electric field.

The effects of thermal diffusion are most apparent in the drift region of the first drift-field detector 110_1, where the charge has been drifting for 10 ns (i.e., curve 410).

[0036] As can be seen from Figure 4A, sub-nanosecond differences between times-of-arrival of light pulses can be easily discerned using centroid detection. Using known diffusion characteristics, it is possible to find the centriod of a charge distribution with high accuracy (e.g., better than a tenth of a nanosecond). Given the start time of the electric field, the position of the centriod of the charge distribution, and the rate of drift in the semiconductor material, the time-of-arrival of the light pulse that gave rise to the injected charge can be determined. Thus, each drift-field detector 110_i in the array 104 can collect information to determine the relative time-of-arrival of a light pulse striking its light sensor 204.

[0037] Figures 4B and 4C show the effects of thermal diffusion on the charge distributions in drift-field detectors 110_1, 110_2, and 110_3. Figure 4B shows the charge distributions 10 ns after the electric field has been removed. As the charge thermally diffuses, the peak amplitude of the distribution decreases. The centroid, however, remains in a fixed position. Figure 4C shows the normalized charge distributions 100 ns after the electric field has been removed. As illustrated, the charge distributions almost completely overlap, and thus make it difficult to distinguish among their positions to determine the times-of-arrival. In one embodiment, the charge distribution in each drift region 202 is transferred into its respective analog storage device 112_i within 5 to 20 ns after the electric field is removed.

[0038] The length of the drift region 202 and the magnitude of the electric field dictate the time t_{stop}. In the above example, the drift region 202 of each the drift-field detectors 110 was 100 μm and the electric field was 10 V/100 μm. In that example, each of the drift-field detectors 110 could only be activated for 10 ns after the first signal of interest arrived. If they were activated for any longer, charge would begin to drift out of the drift region 202, and time-of-arrival data for the first incoming reflected light pulses would be lost. In that example, the drift-

field detector array 104 can resolve centimeters of resolution with a total range of about 30 meters. Thus, the length of the drift field 202 and the magnitude of the electric field dictate the maximum depth range of the system 100. The time t_{start} controls where the range begins. That is, the range is a window that can be moved forward and away from the system 100 by controlling when the drift-field detectors 110 are activated relative to the emission of light pulses 124. The resolution and depth range can be zoomed by varying the magnitude of the electric field (by varying the voltage of variable voltage supply 206). For example, the electric field can be set such that the drift-field detector array 104 can resolve millimeters of resolution with a total range of about 3 meters. Additionally, particular groups of drift-field detectors 110 can have a higher or lower magnitude electric field than other groups by employing selective control via control circuitry 107. In one embodiment, selective control is implemented via CMOS multiplexers as described above. In such an embodiment, the drift-field detector array 104 would allow the system 100 to zoom in on particular portions of the target 118.

[0039] The above discussion assumed that three light pulses differing in times-of-arrival struck three different drift-field detectors 110_1, 110_2, and 110_3. Figure 5 illustrates a case where multiple light pulses that differ in times-of-arrival strike a single drift-field detector. As shown, light source 102 transmits an illuminating pulse 502 towards the target 508. Drift fields 504_1, 504_2, and 504_3 for three drift-field detectors are shown, having fields of view 506_1, 506_2, and 506_3, respectively. The field of view 506_2 for the second drift field 504_2 covers portions of the target 508 having two different depths Z_1 and Z_2. Thus, drift field 504_2 will contain two discernible charge distributions. This result is inherent in the design of the present invention. Thus, the present invention can advantageously discern multiple distances within a single drift-field detector using a signal illuminating pulse. Resolving multiple distances within a single drift-field detector significantly enhances the processing of three-dimensional data.

[0040] Figure 3 depicts a block diagram showing one embodiment of analog storage devices 112. The analog storage devices 112 comprise M vertical CCD

registers 302_1 through 302_M (collectively 302), a horizontal CCD register 304, and an electrometer 308. Each of the vertical CCD registers 302 comprises a multiplicity of bins 310 for storing charge. The horizontal CCD register 304 also comprises a multiplicity of bins 312. An MxN array of drift-field detectors 110 is shown. Each column of drift-field detectors 110 is associated with one of the vertical CCD registers 302. Each of the vertical CCD registers 302 is further coupled to the horizontal CCD register 304. Operation is in accordance with what is known in the art as interline transfer. The charge distribution in each drift region is first transferred to bins 310 substantially as described above with respect to Figure 2. Then, for each of the vertical CCD registers 302, the charge in a first set of bins 310 associated with the first drift-field detector 110 in the column is transferred to bins 312 in the horizontal CCD register 304. The horizontal CCD register 304 comprises at least enough bins 312 to hold charge data from a detector in each of the vertical CCD registers 302. All the charge in each of the vertical CCD registers 302 is then moved down in charge-transfer fashion to fill the empty bins.

[0041] Once this first set of charge is in the horizontal CCD register 304, this charge is transferred using standard CCD practice to be detected by electrometer 308. The electrometer 308 can comprise a floating diffusion electrometer stage known in the art. The electrometer 308 converts charge to voltage, which then can be read out by the processor 106 through control circuitry 107 of Figure 1. The processor 106 then displays the information on display 108. This process repeats until all of the charge is read out from the analog storage devices 112.

[0042] The embodiment shown in Figure 3 for the analog storage devices 112 allows the present invention to bin multiple fields from the drift regions. Specifically, a first illuminating pulse illuminates the target as described above with respect to Figure 1. The drift-field detectors 110 detect the reflected light pulses, and the analog storage devices 112 store the charge distributions. At this point, however, the vertical CCD registers 302 are not read into the horizontal CCD register 304. A second illuminating pulse illuminates the target and the process is repeated. After each reflected pulse, the charge in each drift

region drifts to give time resolution, the field is removed, and the charge pattern is loaded into the vertical CCD register 304. The summing of charge, or "charge binning", in the analog storage devices 112 is substantially noiseless. In this embodiment, the time separation of the illuminating pulses must be greater than the maximum drift time plus the transfer time from the drift regions to the analog storage devices 112. Charge binning allows the present invention to detect reflected light pulses that are very weak thereby increasing system sensitivity.

[0043] The use of CCD registers for the analog storage devices 112 also provides very low readout noise capability. The CCD registers can be cooled using thermo-electric coolers (not shown) so that the binning of charge and readout can be carried over tenths of seconds. It is important to note that the slower the charge is read out from the analog storage locations 112, the less noise is introduced into the system. The present invention advantageously allows for very slow readouts when imaging in noisy environments.

[0044] In yet another embodiment, the signal-to-noise ratio of the X and Y resolution information provided by array 104 can be further improved by charge binning the charge distribution after the depth information has been obtained. Specifically, the invention operates as described above to obtain a three-dimensional image. That is, the charge distribution from each of the drift-field detectors 110 is stored in the analog storage devices 112. Charge binning can be used to increase system sensitivity. Then, a non-destructive readout of the charge distributions is performed to obtain the information necessary to display the depth of the scene. Then, the charge distribution for each of the drift-field detectors 110, spread over multiple bins in the vertical CCD registers 302, can be binned into a single CCD stage (e.g., a single CCD stage in horizontal CCD register 304) representing a pixel associated with the X and Y position of that particular drift-field detector 110. This second stage of charge binning increases the signal-to-noise ratio for a second readout of the two-dimensional information. That is, the charge distributions are summed so as to represent a pixel of the scene without depth information. In another embodiment, only a subset of the drift-field detectors have their charge binned into a single CCD stage. In this embodiment, some of the three-dimensional information is saved

for further processing. Again, this selective control can be implemented using control circuitry 107 comprising a CMOS multiplexer as described above.

[0045] FIG. 6 is a plan view depicting another exemplary embodiment of a drift field detector 600. The drift field detector 600 may be used as a pixel in a detector array of an imaging system, such as the imaging system 100 of FIG. 1. The drift field detector 600 comprises a substrate 602 having a light sensor 604, a drift region 606, and a readout sensor 608. The light sensor 604 comprises an elliptically shaped active area (e.g., circular active area) defined by an outer edge 610 and an inner edge 612. The drift region 606 comprises an elliptically shaped semiconductor drift region defined by an outer edge 614 and an inner edge 616. The drift region 606 is circumscribed by the light sensor 604 such that the outer edge 614 of the drift region 606 is proximate the inner edge 612 of the light sensor 604. A plurality of gates 618_1 through 618_N (collectively referred to as gates 618) are disposed atop the drift region 606, where N is an integer greater than one. The gates 618 are configured as spaced apart concentric ellipses. The readout sensor 608 is circumscribed by the drift region 606 and the innermost gate 618_N, and is proximate the inner edge 616 of the drift region 606. Due to the elliptical geometry, the drift field detector 600 exhibits a larger fill factor when compared to a drift field detector having a rectangular geometry.

[0046] In operation, the light sensor 604 generates a charge proportional to the amount of photon energy incident on the active area defined by the inner and outer edges 610 and 612. The light sensor 604 may comprise any type of light sensitive detector known in the art, where the choice of light sensitive detector is dictated by the particular wavelength of light to be detected. The generated charge is injected into the drift region 606. A voltage differential is established across the gates 618 to produce an electric field within the drift region 606.

[0047] The injected charge moves inward within the drift region 606 under the influence of the electric field at a rate determined by the magnitude of the electric field combined with the carrier mobility. A charge distribution is thus formed within the drift region 606 having a certain shape and position

determined by both the electric field and thermal diffusion. The electric field is then removed from the drift region 606 in response to various trigger events. For example, the electric field may be established for a pre-defined period of time. Alternatively, the electric field may be deactivated in response to detection of charge at the readout sensor 608. If the drift field detector 600 is part of an array, then the electric field may be deactivated in response to detection of charge at a readout sensor of another one of the drift field detectors in the array.

[0048] In any case, when the electric field is removed, the centroid of the charge distribution will remain fixed within the drift region 606, but the shape will continue to disperse due to thermal diffusion. The dispersion is stopped by applying different voltages to the gates over the drift region. In one embodiment of the invention, the charge distribution is binned within the drift region 606 by establishing an alternating high-low voltage potential across the gates 618. The binned charge distribution (e.g., charge histogram) may then be read out of the drift region 606 using the readout sensor 608. Notably, the binned charge may be transported through the drift region 606 using a particular clocked voltage configuration across the gates 618. The charge distribution may be used to determine time-of-arrival of a light pulse, as described above.

[0049] FIG. 7 is a cross-sectional view of an exemplary embodiment of the drift field detector 600 taken along the line 7—7 of FIG. 6. Elements of FIG. 6 that are the same or similar to those shown in FIG. 7 are designated with identical reference numerals and are described in detail above. In this exemplary embodiment, the substrate 602 comprises p-type silicon. The light sensor 604 illustratively comprises a PN photodiode having an exposure gate 702, an n+ region 704, and a transfer gate 706. The n+ region 704 comprises the active region of the light sensor 604. The drift region 606 comprises an n-type buried-channel 708 formed within the p-type silicon of the substrate 602. The gates 618 of the drift region 606, and the gates 702 and 704 of the light sensor 604, are separated from the substrate 602 by a layer of silicon dioxide (SiO_2) 703, as is known in the art. The readout sensor 608 illustratively comprises a floating

diffusion sense node 710 defined by an n+ region within the buried-channel 708.

[0050] In response to the incident light, photo-generated charge is collected in a potential well formed by the PN junction. The exposure gate 702 controls whether photo-generated charge is collected and acts as an "electronic shutter" for the drift field detector 600. After a pre-defined integration period, a bias may be applied to the transfer gate 706 to inject the collected charge from the light sensor 604 to the drift region 606. As described above, an increasing voltage potential is established across the gates 618 to generate an electric field within the drift region 606. The biasing of the light sensor 604 and the drift region 606 may be controlled via bias circuitry 712. The injected charge drifts under the influence of the electric field and, upon the occurrence of the desired triggering event, the charge is binned by applying an alternating high-low voltage potential across the gates 618 to form a charge distribution. The charge distribution is then read out via the sense node 710 using readout circuitry 714. Notably, a clocked voltage potential may be applied to the gates 618 in order to transfer the charge distribution in a charge-coupled manner to the sense node 710.

[0051] FIG. 8 is a plan view depicting yet another exemplary embodiment of a drift field detector 800. The drift field detector 800 may be used as a pixel in a detector array of an imaging system, such as the imaging system 100 of FIG. 1. The drift field detector 800 comprises a substrate 802 having a light sensor 804, a drift region 806, and a readout sensor 808. The light sensor 804 comprises an active area defined by an outer edge 810 and an inner edge 812. The drift region 806 comprises a trapezoidal-shaped semiconductor drift region defined by an outer edge 814 and an inner edge 816. The outer edge 814 of the drift region 806 is proximate the inner edge 812 of the light sensor 804. A plurality of gates 818_1 through 818_N (collectively referred to as gates 818) are disposed atop the drift region 806 in spaced apart relation, where N is an integer greater than one. The readout sensor 808 is proximate the inner edge 816 of the drift region 806. Due to the trapezodial geometry, the drift field detector 800 exhibits a larger fill factor when compared to a drift field detector having a rectangular geometry. To further increase the fill factor, a microlens (see FIG. 9) may be

disposed atop the active region of the light sensor 804 to focus the light onto the active region.

[0052] In operation, the light sensor 804 generates a charge proportional to the amount of photon energy incident on the active area defined by the inner and outer edges 810 and 812. The light sensor 804 may comprise any type of light sensitive detector known in the art, where the choice of light sensitive detector is dictated by the particular wavelength of light to be detected. The generated charge is injected into the drift region 806. A voltage differential is established across the gates 818 to produce an electric field within the drift region 806, substantially as described above. The injected charge moves inward within the drift region 806 under the influence of the established electric field and a charge distribution is formed within the drift region 806 having a certain shape and position. The electric field is then removed from the drift region 806 in response to a desired trigger event, similar to the embodiments of drift field detectors described above.

[0053] When the electric field is removed, the charge distribution will remain fixed within the drift region 806, but the shape will continue to disperse due to thermal diffusion. The dispersion is stopped by applying different voltages to the gates over the drift region. In one embodiment of the invention, the charge distribution is binned within the drift region 806 by establishing an alternating high-low voltage potential across the gates 818. The charge distribution may then be read out of the drift region 806 using the readout sensor 808. Notably, the charge may be transported through the drift region 806 using a particular clocked voltage configuration across the gates 818. The charge distribution may be used to determine time-of-arrival of a light pulse, as described above.

[0054] FIG. 9 is a cross-sectional view of an exemplary embodiment of the drift field detector 800 taken along the line 9—9 of FIG. 8. Elements of FIG. 8 that are the same or similar to those shown in FIG. 9 are designated with identical reference numerals and are described in detail above. In this exemplary embodiment, the substrate 802 comprises p-type silicon. The light sensor 804 illustratively comprises a PN photodiode having an exposure gate 902, an n+

region 904, and a transfer gate 906. The n+ region 904 comprises the active region of the light sensor 804. In one embodiment, a microlens 905 may be disposed above the active region of the light sensor 804 to increase the fill factor of the drift field detector 800.

[0055] The drift region 806 comprises an n-type buried-channel 908 formed within the p-type silicon of the substrate 802. The gates 818 of the drift region 806, and the gates 902 and 904 of the light sensor 804, are separated from the substrate 802 by a layer of SiO_2 903, as is known in the art. The readout sensor 808 illustratively comprises a floating diffusion sense node 910 defined by an n+ region within the buried-channel 908. The light sensor 804 and the drift region 806 operate in a manner similar to the light sensor 604 and drift region 606 described above with respect to FIGs. 6 and 7. Notably, the biasing of the light sensor 804 and the drift region 806 may be controlled via bias circuitry 912. The charge distribution may be read out via the sense node 910 using readout circuitry 914. The triangular drift region 806 occupies less area than a rectangular drift region, allowing the control circuitry (e.g., bias circuitry 912 and readout circuitry 914) to be placed within a saved area 850 (FIG. 8).

[0056] For purposes of clarity by example, the drift field detectors 600 and 800 have been described as having a p-type silicon substrate. Those skilled in the art will appreciate, however, that the substrate may be formed of n-type silicon. In such an embodiment, the buried-channel is formed of p-type silicon, the light sensor includes a p+ region, and the sense node includes a p+ region. In addition, although the light sensors 604 and 804 have been described as a PN photodiodes, those skilled in the art will appreciate that other types of light sensors may be employed, including other types of silicon photodetectors (e.g., PIN photogate), as well as a platinum silicide detectors, a III-IV detectors, and the like along with the appropriate readout circuitry. Furthermore, those skilled in the art will appreciate that other types of readout sensors 608 and 808 may be used, including floating gate readouts, current amplifiers, and transimpedance amplifiers. Moreover, although aspects of the invention are described with respect to elliptical and trapezoidal drift regions, those skilled in the art will appreciate that drift regions of other shapes may be employed. In

general, a drift field detector of the invention includes a drift region having an outer edge and an inner edge, where the volume of the drift region decreases from the outer edge to the inner edge.

[0057] A method and apparatus for generating charge from a light pulse has been described. A drift field detector includes a light sensor and a semiconductor drift field. The light sensor generates electric charge in response to a light pulse and the charge is injected into the drift region. Under influence of an electric field, the photo-generated charge drifts through the drift region. The electric field is deactivated in response to a desired triggering event. A charge distribution within the drift region is either stored in an analog storage device and read out, or is read out directly from the drift region using a sense node. By determining the distance the photo-generated charge drifted within the drift region, the time-of-arrival of the light pulse may be determined with respect to the time the electric field was deactivated with sub-nanosecond accuracy. In one embodiment, the drift field detector is used within an array of detectors. A light pulse illuminates a target and the reflected portions of the illuminating pulse are focused onto the array. The relative times-of-arrival of the different reflected portions may be identified and used to determine the depth and contours of the target.

[0058] While the foregoing is directed to embodiments of the present invention, other and further embodiments of the invention may be devised without departing from the basic scope thereof, and the scope thereof is determined by the claims that follow.